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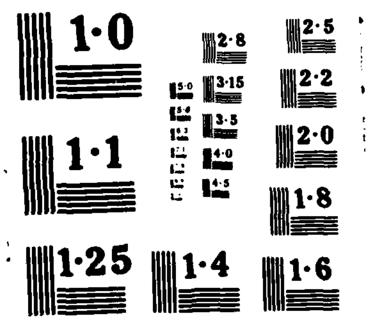
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Structures Report 424

THE INFLUENCE OF LOAD CYCLE RECONSTITUTION ON FATIGUE BEHAVIOUR

by

J.M. FINNEY and F.G. HARRIS

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SUMMARY

Fatigue experiments have been conducted to assess the influence of the method of reconstituting a load sequence from a range-pair counted load spectrum for a fighter aircraft. In addition to the original flight-by-flight sequence, several quite-structured reconstituted sequences and random reconstituted sequences were used, all sequences having identical range-pair counts. There was little or no difference in crack propagation lives or total lives of two specimen geometries for the several structured sequences which were designed to give the extremes in crack growth life. There was, also, no significant difference in crack propagation lives for specimens tested under the flight-by-flight and random sequences. Crack growth under the more-structured sequences was significantly slower than under the more-fluctuating sequences (random and flight-by-flight), though the maximum difference of 1.59:1 is small relative to other uncertainties in fatigue life assessment. These results provide a basis for implementing the Aircraft Fatigue Data Analysis System which utilizes strain range-pair counting.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
P. O. Box 4331, Melbourne, Victoria, 3001, Australia.

CONTENTS

1. INTRODUCTION

Common experience affirms that the more force we exert on a body, the more severely it is influenced. Hooke's law and the principle of superposition are well known examples of this in static stressing. Fatigue behaviour is, mostly, similar — the larger the cyclic stress, the shorter the life. An exception, however, may be found with variable-amplitude loading where an **increase** in crack propagation life may occur when an **extremely high** tensile load is inserted into the sequence. The increase in life, dependent on many factors, can be quite large, in some cases more than an order of magnitude.

Most recorders for continuous monitoring of loads experienced by aircraft structures retain no sequence information and utilization of the load records for fatigue assessments often will require a 'reconstitution' of the loading sequence from which the condensed data were recorded. This reconstitution is obviously a prerequisite to carrying out a fatigue test to a specific load spectrum and the question of interest is whether the life could be influenced by the particular reconstitution used. Given the possible magnitude of the load sequence effect noted above the method of cycle reconstitution could be crucial to the goal of producing the same fatigue behaviour as would have been obtained by test under the original sequence. (The original sequence may be unknown however, because unrecorded.) The same comments apply to calculating crack growth.

It is apparent that experiment is necessary to test the suitability of any scheme of reconstitution by comparing results using a known original sequence with those using a reconstituted sequence. It is here that a further complexity arises, since the reconstitution of any sequence requires, as a first step, the counting of cycles of the original sequence (by this means eliminating the time information), and there is a multiplicity of methods for counting cycles. Attempts to determine the proper or correct method of reconstitution could thus be fruitless because it is quite possible that several combinations of the cycle counting and reconstitution methods would give the same fatigue behaviour as the original sequence.

Because of this complexity the experiments presented in this report are confined to examining the premise that, within the constraints of a particular scheme for counting cycles, the load sequence is significant. The particular aim was to reconstitute so as to obtain the upper and lower bounds to fatigue crack propagation life. If the range of lives obtained is large, say greater than 10:1, then the matter of specific methods of reconstitution is important; but if the range is, say, less than 2:1, we may assert that reconstitution adds only marginally to scatter in life.

Much of the load interaction research in fatigue crack propagation has used rather simple specimen geometries and quite extreme sequences, e.g. a single overload inserted into an otherwise constant-amplitude sequence imposed on a centre-cracked plate. There is no doubt that with extreme sequences the method of reconstitution could greatly affect the crack growth life. It is not evident, however, that similar drastic effects will be found with realistic loading spectra and with more-complex specimens. The experiments reported here use a flight-by-flight fighter sequence and specimens which represent a section of a wing spar. Additional tests with the same reconstituted sequences applied to centre-cracked specimens allow any specimen geometry effect to be determined, and the opportunity was taken with these specimens to determine any stress scaling effect.

2. SEQUENCE AND CYCLE COUNTING

The basic load sequence was that used in testing a Mirage IIIO wing at Aeronautical Research Laboratories (ARL) (Ref. 1). It is a flight-by-flight sequence, typical of that for a fighter aircraft, covering 500 flights, and consisting of 108,920 turning points per program. It was obtained from a strain gauge on the wing main spar and the peaks and troughs were, roughly, continuously variable, with the maximum strain corresponding to a 7.5g load.

Cycle counting this sequence utilized the range-pair method (Ref.2) and there were two main reasons for this choice. First, it is not only a popular and readily-applied method but it has the fundamental significance of being related to the plastic strains which occur in fatigue cycling (the range-pair, rainflow, and hysteresis loop methods of counting cycles are practically equivalent (Ref.3)). Second, the Aircraft Fatigue Data Analysis System (AFDAS), conceived by ARL and developed by British Aerospace Australia (Ref.4), and being implemented as the main load recorder in Royal Australian Air Force aircraft, counts strain range-pairs during aircraft operation. Because AFDAS records cycles at discrete rather than continuous levels of load, the peaks and troughs in the Mirage Wing test sequence were rounded to the mid-points of a counting grid resulting in 14 discrete and uniformly-spaced levels over the sequence. This 'discretized' sequence is hereafter referred to as the flight-by-flight (f-b-f) sequence.

The results of the range-pair count on this f-b-f sequence are shown in Fig. 1. The 14 levels are designated with microstrain values which indicate the magnitudes of the strains at one location in the wing spar and are included only to show the zero position in relation to the 14 levels. The complete set of range-pairs was determined in one pass through a computer program (Ref.2). Pairing of the residual turning points is achieved in the program by employing artificially-large end points which has the effect of pairing the largest peak (level 14) with the largest trough (level 1). This table is the basis of all the reconstitutions.

3. RECONSTITUTIONS

From any range-pair table it is possible to generate a large number of different sequences which, when counted, all return the original table, and in the present work two sequences were developed to accelerate crack growth and two to retard it.

3.1 Sequences A1 and R1

Two simple reconstitutions were developed first, an acceleration sequence denoted A1 and a retardation sequence denoted R1. Sequence A1 followed the acceleration principle — 'precede the largest loads with the smallest loads'. The small loads produce a sharpened profile and a limited zone of residual compressive stress at the crack tip, thus promoting conditions for the following high loads to produce larger-than-normal crack growth increments.

Figure 2 shows the application of this principle to the range-pair table. The sequence commences with the highest peak and trough and follows successive diagonals, each of constant load range but decreasing mean load, until the smallest range and mean are reached. Figure 4(a) illustrates the resulting sequence and indicates the typical features expected to result in crack growth accelerations. The main feature is that the smallest loads in one program length are followed immediately by the largest loads in the next program. The numbers noted against each load range indicate the number of repetitions of that range before proceeding to the next range. (The numbers shown in Fig 4 (a) are not always identical with those shown in the range-pair table (Fig. 2). This arises because range-pair counting is sequence-dependent; explanatory details are discussed with later reconstitutions. These remarks apply to the four sequences shown in Figs 4 and 5. When using the range-pair table to discuss the creation of the various reconstituted sequences however, the numbers from the table are quoted even though the actual numbers in the created sequence were sometimes slightly different).

Promotion of crack growth retardations, to produce sequence R1, used the principle — 'follow the largest loads with the smallest loads'. The large loads produce crack tip blunting and an extensive field of compressive residual stress at the crack tip resulting in less-than-normal crack increments from the succeeding lower loads. This principle is exactly the reverse of that for accelerating crack growth and a mirror image of sequence A1 was adopted. Figure 3 shows the reverse order and direction of following diagonals in the range-pair table, and Fig. 4(b) shows the resulting sequence and the features which should give crack growth retardations.

3.2 Sequence A2

The second acceleration sequence, denoted A2, was a development of A1 and utilized three features known to accelerate crack growth.

i. Precede the largest loads with the smallest loads (as for sequence A1).
ii. Randomise or continuously fluctuate successive load levels.
iii. Reduce retardation by:
   a. following the largest positive peaks immediately with a negative trough,
   b. gradually decaying successive peaks following the largest peaks.

Item ii is founded on surface and fractographic crack growth measurements. For example, McMillan and Pelloux (Ref. 5) have shown that random load crack growth rates are higher (about 50%) than those for well-ordered blocks of constant-amplitude cycles. Also, Ryan (Ref. 6) has demonstrated with blocks of constant-amplitude cycles applied in various orders, that peak load levels invariably give accelerated crack growth compared with growth at the same levels applied continuously. Even in sequences for which the prominent effect at most load levels was retardation of the crack growth, the peak levels gave acceleration, apparently due to the fluctuating nature of the blocks.

Although, on the average, block loading gives longer fatigue lives than does random loading (Ref. 7), this occurs mostly with long block lengths (tens of thousands of cycles, or more). Shorter lives, i.e. more acceleration or less retardation, tend to be found with block loadings in which the peak values of the alternating load change frequently. Randomisation or continuous fluctuations will produce frequent low or negative loads thus keeping the crack tip somewhat sharp and the residual compressive stress level low. As the acceleration period commences earlier and is of much shorter duration than the retardation period for a given step change, continuous fluctuations are likely to enhance acceleration.

The preventative measures of item iii are also based on experimental data and the explanation of (a) is usually that the important crack tip residual stresses are those from the last large load excursion, whether negative or positive (Ref. 8). Retardations rely upon successive peaks being very much lower than a preceding large peak load – if the load changes are gradual the retardation is greatly reduced, leading to (b) above.

Figure 5(a) illustrates how the principles were applied in producing sequence A2 which is a compromise between randomised and gradually-decaying patterns. The range-pair numbers, particularly of the higher load ranges, restrict how extensively the fluctuation scheme can be implemented, and the details are given in Appendix 1.

3.3 Sequence R2

The second retardation sequence, R2, also used three features for retarding crack growth.

i. Follow the largest peak in the sequence with all peaks expected to give no subsequent crack growth, i.e., utilize the phenomenon of crack arrest.
ii. After the application of a large peak load take account of the phenomenon of delayed retardation in order to minimise subsequent growth rates.
iii. Apply multiple rather than single large-peak loads to enhance the amount of retardation.

Item i. is based on theory and experiment. According to the Willenborg et al. (Ref. 9) model of crack growth retardation, crack arrest occurs when the overload ratio (ratio of peak of high positive load to peaks of subsequent constant-amplitude cycles) is equal to or greater than two. Probst and Hillberry (Ref. 10) have found that, for a number of different high stresses applied to 2024-T3 aluminium alloy, the ratio for crack arrest was 2.3. Sequence R2 commenced with the largest load peak possible (level 14) and was followed by all peaks with magnitudes less than half the largest peak. These subsequent loads commenced with the lowest peaks and were applied in range-pair table blocks. This procedure is illustrated in Fig. 8 and it concluded with peak level 8, giving overload ratios no smaller than about 2.5. It was thus assumed that, by this load sequencing, no crack growth would result from any of the peaks up to level 8.

Item ii. used information from the literature (Ref. 11) to calculate the number of cycles, after an overload, to produce the minimum growth rate. The pattern followed was to apply the highest possible peak overload (actually multiple overloads were used – item iii. – to enhance the retardation) and to follow this by the smallest peaks available until the calculated minimum growth rate was achieved, then repeat with remaining range-pairs until all are used. Appendix 2 provides the details of this procedure. Figure 8 indicates the complete pattern followed for R2 and Fig. 5(b) illustrates the actual sequence.

4. EXPERIMENTS AND RESULTS

4.1 Simulation Specimens

These specimens, shown in Fig. 11, simulate an area of the rear flange of the Mirage IIIO wing main spar which features a heavy section with bolted connections and load transfer. They were made from three 48 mm-thick rolled plates, all from the one batch of A7-U4SG-T651 aluminium alloy, with the loading axis in the rolling direction. The material specification is the current version of the Mirage material and is equivalent to the US alloy 2214. The tensile and fracture properties of the plates are given in Table 1.

The fatigue tests were made in a computer-controlled electrohydraulic machine at a gross-area stress (excluding side plates) of 30.4 MPa/g — the level 14 load was equivalent to 7.5g. The average cyclic frequency was 5.5 Hz and a sinosoidal-like waveform was used. Several specimens were tested under the f-b-f sequence and under each of the reconstituted sequences A1, A2, R1, R2, and the total lives are shown in Table 2. Pairwise comparisons and an analysis of variance for these results, using a significance level of 0.05, showed that there is no significant difference between the means or the variances of log total life for the five sequences.

All specimens fractured through one of the end bolt holes and Fig. 12 illustrates the general morphology. Figure 13 shows a typical striation sequence used to identify the program crack increments. Crack growth data, by means of fractography, were obtained for one specimen from each of sequences A1, A2, R1, R2 (despite intensive effort the f-b-f fractures were not amenable to fractographic analysis), and the number of programs for the crack to grow from 0.3 mm to 8.0 mm in depth was determined for each specimen (see Table 2). The ratio of shortest to longest crack life is practically the same as that for the total lives of the same specimens. This, together with limitations on the amount of crack growth data, gives an expectation that the lack of sequence effect found on total life will apply also to crack growth life.

4.2 Centre-Cracked Specimens

Centre-cracked specimens were tested under A2 and R2 sequences only, to ascertain whether the lack of sequence effect on total life for the simulation specimens applied to crack propagation life and whether it depended on either geometry or stress level. The specimens were made from the same plates as the simulation specimens and measured 12 mm x 80 mm x 300 mm, with a central spark-machined slit 0.015 mm wide by 12 mm in length. The tests were made in accordance with the ASTM standard E647-81 (for constant-amplitude crack growth data) where applicable. The test frequency was again an average of 5.5 Hz, and two gross-area stress levels of 11.0 and 17.0 MPa/g were used to cover a range of test lives. Three specimens were tested under each sequence/stress level combination.

Crack growth was measured on one face using a microscope and a reference grid photographically reproduced onto the specimen. Corrections for crack curvature were made, when necessary, after examining the fractures. All crack length measurements were made at the completion of a program and the results are shown in Figs 14, 15. Comparisons of average best-fit curves covering the two sequences and two stress levels are shown in Fig. 16. From curves fitted similarly to each test result, crack growth lives at several crack lengths were determined (Table 3) and from these data statistical tests were made with the following conclusions, all based on a significance level of 0.05.

i. For both stress levels there is no significant difference between the variances in crack growth life for sequences A2 and R2.

ii. At 17.0 MPa/g, covering lives up to about 10 programs (5000 flights), retardation sequence R2 gives significantly **faster** crack growth than acceleration sequence A2. The difference between the average crack growth curves is small, however, being less than 15%.

iii. At 11.0 MPa/g, covering lives up to about 40 programs (20,000 flights), there is no significant difference between the A2 and R2 average crack growth curves.

5. DISCUSSION

The experimental result that there is little or no difference in crack growth lives (and total lives) between sequences specially reconstituted to give extremes in crack propagation life was not expected. Moreover this is not because of a fortunate choice of test conditions, since the same result was obtained at two different stress levels and with two different specimen geometries. It could be argued (in hindsight) that this result is more likely with a fighter spectrum than with a transport spectrum where the fewer large peaks could exert a more disproportionate influence, depending on their location in the sequence, and therefore it is not a result to be generalised. If this were so, however, and reconstitutions gave **significant** effects with a transport spectrum, at least **some** influence of sequence should be evident with a fighter spectrum, yet there is none.

There is plentiful evidence that sequence affects crack growth life for quite arbitrary block programmed sequences. For example, Schijve (Ref. 16) found a 2:1 difference in crack propagation lives between Hi-Lo and Lo-Hi ordering of a 40,000 cycle blocked sequence. Range-pair counts on the Hi-Lo and Lo-Hi sequences would be identical. Of more immediate importance is Schijve's finding that when the average number of cycles in the program was 40 (there were actually 10 different flights represented, each with a different number of cycles), the Hi-Lo sequence gave only a 20% longer crack growth life than the Lo-Hi sequence. In addition, the 40-cycle program gave similar crack growth lives to those under random loading, but the 40,000-cycle program lives were about 2½ times longer. Schijve concluded that sequence effects, and variations in crack growth life, occur only when the changes in load amplitude are infrequent.

Many hundreds of load amplitude changes were applied in the current specimen tests and this, in itself, may partially explain the lack of sequence effect. That is, based on block-program evidence, there may have been a sufficient number of load changes of significant magnitude that the material responded to even the most ordered reconstitution as though it were effectively random. To this must be added the comment expressed in Section 3, that the common number of counts and the range-pair method itself impose quite severe restrictions on the arbitrariness of reconstitution.

Although the results argue strongly for the inconsequence of the reconstitution procedure it is thought that for practical purposes more-randomised reconstitutions would be better accepted. For this reason, and because the f-b-f sequence gave the lowest average life of the simulation specimens (though not significantly lower than the other sequences), a further series of tests was made on centre-cracked specimens under the f-b-f and random sequences. Appendix 3 provides details of the random reconstitutions and, because the process is computer-programmed, a different sequence was produced for each replicate test. All test conditions (apart from sequence) that were used with the A2 and R2 sequence tests were applied to the f-b-f and random sequence tests and the results are shown in Figs 18 and 19. There was no additional scatter in crack growth by using separate random sequences. Average best-fit curves of the experimental crack growth are given in Fig. 20 and are compared with the previous crack growth from sequences A2 and R2. Again, crack growth lives at several crack lengths were determined (Table 4) and statistical tests gave the following conclusions.

i. Crack growth lives under the f-b-f and random sequences are practically identical.
ii. Crack growth under the more-structured sequences (acceleration and retardation) is significantly slower than under the less-structured more-fluctuating sequences (random and f-b-f).
iii. The maximum spread in average crack growth lives is between those under the acceleration and random sequences at both stress levels and is an average of 1.59:1 at 11.0 MPa/g and 1.51:1 at 17.0 MPa/g.

These further experimental results were also unexpected. The dominant factor producing the variations in crack growth lives with sequence that did occur was obviously the frequency of load level changes, and the sequences designed for crack growth extremes were apparently deficient in this respect. The topic of load sequence effects in fatigue crack propagation has been dominated by experiments in which a single overload (sometimes multiple overloads) is applied once in an otherwise constant-amplitude sequence. Very large changes in growth rate may follow the overload and it is these changes which not only produced the expectation that crack growth life will depend on the reconstitution, but provided the general rules for the various extreme reconstitutions.

The experimental results can be interpreted as indicating either:

i. that retardations and accelerations of crack growth, if they occur, have a negligible influence, or

ii. that significant retardations and accelerations may occur but they average out over lengthy realistic sequences.

Whichever the case, if the various sequence effect rules were not ill-used, it appears that many of them are inapplicable to aircraft loading spectra. This would raise an interesting problem in crack growth prediction where retardation models were created specifically to account for the ultra-conservative predictions when sequence effects are ignored.

The fact that sequence A2 gave longer crack growth lives than sequence R2, though significant only at 17.0 MPa/g, is still a puzzle, particularly as A2 contained many more load level changes than R2 (4 times as many based on load range and 17 times as many based on peak load). There is also some difficulty in resolving the f-b-f sequence results in relation to those for the structured sequences A2 and R2 for the two specimen geometries. The centre-cracked specimens gave a significant difference in crack propagation life; the simulation specimens showed no significant difference in total life. Sequence effects, therefore, are either geometry dependent or they are quantitatively different for total life and crack propagation life.

The differences in crack growth lives for the various reconstitutions that were shown to be statistically significant must be viewed in the context of the accuracy of life assessment. Reconstitutions of load spectra data, such as from AFDAS, are used to determine fatigue life, either by calculation or by experiment. Experimental determinations commonly employ only one full-scale test article and a factor, usually between two and four, is applied to the result to allow for scatter. A similar allowance is made on calculated lives, though for crack growth in damage tolerance calculations the factor is applied for assurance of crack detection (Ref. 17). (As a generalisation, however, it is believed that crack growth cannot be predicted confidently to better than a factor of two and, in some cases, the factor may be as high as ten (Ref. 14).) Within this framework the present results indicate only a small effect of reconstitution on life, and therefore they support the use of load recorders such as AFDAS. Though small, the effect may be important in some cases of crack growth assessment and, to be conservative, it is recommended that randomised or flight-by-flight type sequences be utilized.

Detailed fractography over one program length for each of the reconstituted sequences should hold the key to the features of the load sequence which influence fatigue life. The length of the program (108, 920 turning points) makes this task difficult with the present specimens and the incidence of particle fracture and lack of fatigue striations makes it almost impossible. However, some recent fractographic work by Sunder et al. (Ref. 18) has indicated that rainflow (range-pair) counting is interpretable on fatigue fracture surfaces. Unfortunately, their fractographic crack increments determined for the several artificial sequences examined can be interpreted equally with other counting methods, e.g. max peak-max trough pairing. Their work, at least, shows that range-pair counting is not incompatible with their fractographic measurements and similar experiments may uncover a fundamental relationship. If such a relationship exists, the general results of this present work would follow.

6. CONCLUSIONS

1. For a fighter aircraft load spectrum little or no difference was found between the mean fatigue lives of specimens tested under different sequences designed to give the upper and lower bounds of crack propagation life, all sequences having the same range-pair count.
2. The mean total life of specimens simulating part of a wing spar under the flight-by-flight sequence on which the various reconstitutions were based, was not significantly different from the lives under the upper and lower bound designed sequences. There was, however, a significant difference for crack propagation specimens.
3. Crack propagation lives under randomly reconstituted sequences were not different from those under the flight-by-flight sequence.
4. The maximum variation in crack growth mean lives under the various reconstituted sequences was 1.59:1 and is small relative to other uncertainties in fatigue life assessment. The small

influences of reconstitution that were obtained were thought to arise from different frequencies of load level change.

5. Random or flight-by-flight reconstitutions of aircraft load spectra are recommended for either experimental or analytical fatigue assessments.
6. The experimental results provide a sound basis for implementing the Aircraft Fatigue Data Analysis System which utilizes range-pair counting.

7. ACKNOWLEDGEMENTS

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APPENDIX 1

DERIVATION OF ACCELERATION SEQUENCE A2

Figure 5(a) shows the general scheme adopted for sequence A2, and the several features aimed at producing crack growth acceleration are incorporated as follows.

i. Over one program length, covering all entries in the range-pair table, the overall pattern consists of applying the highest load ranges first followed by successively lower ranges until the smallest is reached. This pattern is identical with that of sequence A1 where successive diagonals of the range-pair table were traversed (Section 3), and is aimed at producing abnormally large crack growth increments when the high loads of the following program are applied.

ii. The load sequence was fluctuated as much as possible, retaining the features of i. above for each repeat segment within one program. It is evident from Fig. 5(a) that there are two **main** repeat segments in the one program, both repeating sequence A1 with half the numbers each time. The restriction of two main segments is explicable from the following details. The range-pair table shows that, of the high peaks suitable for commencing a segment, there is only one level 14 peak (and this is used to commence the program) but ample level 13 peaks, 163 in all. The table also shows that, for any load range (i.e. diagonal), the lowest troughs are either levels 1, 2, 3 or 4. Since the range-pair counting technique tends to pair highest and lowest loads, the pairing of these troughs with level 13 can occur only 9, 9, 18 and 16 times respectively, a total of 52, which is a further limit on the number of segments.

   Figure 6 illustrates an even tighter restriction placed on the proliferation of segments, all with the character of sequence A1. When load ranges containing the largest troughs and others containing the largest peaks are broken up into alternating segments, more max peak-min trough pairs occur than otherwise. In practice, with the given range-pair table, three main segments is the most that can be used. With three segments, and excluding pairs of levels 1-13 and 2-13 from the sequence, 8 and 7 of these pairs respectively are obtained in a range-pair count. With four segments the numbers exceed those allowed by the table.

   For each diagonal of the range-pair table traversed in a segment the numbers were further divided by two and the diagonal traversed twice as shown in Fig. 5(a). Not all load pairs in a diagonal were so treated however, there was a trough level, for each diagonal, below which further subdivision would give too many pairs of certain levels. This general procedure of further subdivision could have been continued to produce even greater numbers of fluctuations, but as less and less high level peaks could be involved it was not pursued.

iii. For all of the diagonals traversed, and these commenced at levels 14, 13 or 12, a negative load was applied immediately after the largest-peak group of cycles (always at the beginning) to offset any retardation effect. The negative loads used were at levels of either 1, 2 or 3 and the peak paired with any such negative load was chosen to correspond to the peak level of the following block. This is illustrated in Fig. 7. It was possible to follow this procedure only with the first of the two minor sub-divisions of the numbers in a diagonal. To do otherwise produces too many pairings of levels 1, 2 and 3 with each of the levels 11, 12 and 13.

   In the sequence finally adopted, Fig. 5(a), no level 1-13 or level 2-13 pairs are explicitly included, yet the correct numbers, 9 of both, occur in the range-pair count. A corollary of this is that the numbers of pairs actually applied in some other blocks exceed those in the range-pair table, for example, a total of 20 level 4-13 pairs (in four groups of five) are explicitly applied, but only 16 pairings are obtained in the range-pair count.

APPENDIX 2

CALCULATION OF RETARDED CRACK GROWTH FOR SEQUENCE R2

The phenomenon of delayed retardation of fatigue crack growth after the application of an overload is widely established for metals (Refs 12, 13) and is illustrated in Fig. 9. The crack increment, Δa_d, at which retardation ceases is approximately the overload plastic zone length. The point of inflexion or lowest growth rate occurs at a crack increment, Δa_b, which is typically about 20% of the length of the overload plastic zone. The total number of retarded-growth cycles is N_d and the number of cycles to minimum growth rate is N_b.

Matsuoka and Tanaka (Ref. 11) have modelled the retarded crack growth after the application of a single overload with a retardation parameter, U_r^m, defined as follows:

$$U_r^m = (da/dN)_r/(da/dN)_c \tag{1}$$

and

$$U_r = 1-(s/2)(\Delta a_d/\Delta a_b - 1)(a-a_o)/\Delta a_d \text{ for } O \leqq a-a_o \leqq \Delta a_b \tag{2}$$

or

$$U_r = 1-(s/2)[1-(a-a_o)/\Delta a_d] \text{ for } \Delta a_b \leqq a-a_o \leqq \Delta a_d \tag{3}$$

where
m = Paris exponent
s = overload ratio
c,r = subscripts denoting constant-amplitude and retarded.

The present work extends these equations to deal with the further reduction in growth rates caused by applying multiple overloads. Obviously, $O \leqq U_r^m \leqq 1$, and the strength of the retardation may be defined as $(1-U_r^m)/U_r^m$ which is shown diagrammatically in Fig. 10. The multiple overload effect is assumed to double this ratio, which leads to

$$(da/dN)_{r(m.o.)} = [U_r^m/(2-U_r^m)]_{s.o.}(da/dN)_c \tag{4}$$

where subscripts refer to multiple and single overloads.

Standard crack growth rate data, $(da/dN)_c$, at various load ratios are available (Ref. 14) for the aluminium alloy used in the experiments. With these data and the equations above, crack growth increments can be determined for any combination of multiple overloads and following constant-amplitude cycles. The procedure is as follows.

i. Assume an initial or typical crack length.
ii. Calculate the overload plastic zone length, knowing the overload stress intensity, yield stress and stress state.
iii. Assume or otherwise determine the fraction of the plastic zone length at which the minimum in growth rate occurs.
iv. For the cycle immediately following the overload, determine the crack length increment from equations (2) and (4).
v. If the increment is small compared with the initial crack length, the total increment of crack growth may be determined for a block of constant-amplitude cycles by multiplication.
vi. Repeat the above until the summed crack increment equals the chosen end point, say the minimum in growth rate.
vii. Apply further overloads and repeat the procedure.

The number of consecutive overloads to produce maximum retardation appears dependent on several factors but is of the order of 10 to 100 or more. Eidinoff and Bell (Ref. 15), for example, have found experimentally that the number is 13 for 2219-T851 aluminium alloy. In the present work it was convenient to first use the group of nine level 1-13 loads as the highest overloads available. Assuming $\Delta a_b/\Delta a_d = 0.2$, a typical figure (Ref. 12), and that the crack length is typically 1.5 mm, crack increments, as fractions of Δa_d, were calculated for each block of constant-amplitude cycles commencing with the lowest peak level available (level 9). When the summed increments equalled $0.2\Delta a_d$, the set of nine level 2-13 overloads was utilized and the procedure repeated. After the eighteen level 3-13 loads were specified as overloads the subsequent calculated crack increments reached only to about $0.15\Delta a_d$ before all range-pair table entries had been used.

APPENDIX 3

RANDOM RECONSTITUTIONS

The principle of random reconstitution is simply the inverse of the counting method. Figure 17 shows the essence of the range-pair counting method, namely, *if* two turning points are contained within preceding and succeeding turning point levels, they constitute a range-pair. Although 'one-pass' computer programs are available for range-pair counting it is conceptually convenient to consider multi passes through a sequence, each pass removing successively larger turning point ranges. The reverse of this process is used in the development of a random reconstitution.

Figure 17 shows the addition of a turning-point pair to a sequence in such a way that the pair will be counted as a range-pair. Thus, by commencing with the largest peak and largest trough (levels 14, 1 in the present case), any other pair fitted between these extremes will be counted as a range-pair. The procedure then is to insert successively lower turning-point ranges into randomly-selected locations. Each added pair provides two more locations in which it is possible to place the next pair. The insertion sequence followed the diagonals of the range-pair table, proceeding from the largest available range and mean of load.

It is clearly not ideal to commence with only the largest peak and trough, for that would consign them to the beginning or end of the reconstituted sequence. To allow a greater degree of randomness, and because technically more precise, it is preferable to commence with the set of turning points remaining after counting the original sequence. This set will contain the largest peak and trough and is normally a diverging-converging pattern of load range. The residuals for the flight-by-flight sequence were as follows and were used to commence the computer program for random reconstitutions:- level 4-7-3-12-2-13-1-14-1-8-3-7-4.

TABLE 1

Tensile and fracture properties of A7-U4SG-T651
48 mm thick rolled plate (batch serial GT)

a. Static Tensile

	Specification	GT
0.1% proof stress (MPa)		449.5
0.2% proof stress (MPa)	390	455.2
Ultimate tensile strength (MPa)	450	497.1
Elongation (%) ($5.65\sqrt{A}$)	5	11.4

b. Fracture Toughness — 25 mm thick LT specimens

	GT
Fracture toughness, K_{IC} ($MPam^{1/2}$) (average of 5 tests)	32.4
Standard Deviation ($MPam^{1/2}$)	1.8

TABLE 2

SIMULATION SPECIMEN TEST RESULTS

Sequence Description	Specimen Number	Total Life (programs)		Log. Average Life (programs)
Flight-by-flight	GT1AF1	10.35		12.13
	GT2AK1	11.61		
	GT3AF1	12.07		
	GT3AL1	13.38		
	GT2AA1	13.54		
Acceleration, A1	GT1AM1	12.03		14.36
	GT2AG1	12.03		
	GT1AL1	14.01		
	GT1AA1	14.01	(6.0)*	
	GT1AG1	17.17		
	GT2AC1	18.01		
Acceleration, A2	GT3AK1	9.50		13.01
	GT3AG1	10.51		
	GT3AE1	11.01		
	GT1AD1	13.50	(8.0)*	
	GT2AL1	14.50		
	GT1AK1	14.51		
	GT2AD1	15.01		
	GT2AF1	17.50		
Retardation, R1	GT1AE1	11.99		14.78
	GT1AJ1	12.00		
	GT1AB1	13.99		
	GT2AM1	16.99		
	GT3AB1	16.99		
	GT2AB1	17.95	(7.1)*	
Retardation, R2	GT1AC1	10.98		13.22
	GT3AD1	10.99		
	GT2AE1	11.97		
	GT3AJ1	11.99		
	GT3AA1	14.98	(6.85)*	
	GT2AJ1	15.97		
	GT3AC1	17.00		

* crack propagation life (programs) between crack depths of 0.3 mm and 8.0 mm.

TABLE 3

CRACK GROWTH LIVES OF CENTRE-CRACKED SPECIMENS AT SEVERAL CRACK LENGTHS FOR SEQUENCES A2 AND R2

17.0 MPa/g

Sequence	Specimen Number	Number of programs at crack length (2a)			
		15 mm	25 mm	35 mm	45 mm
Acceleration, A2	GT1AP1	1.49	6.67	9.03	10.02
	GT3AN2	1.73	7.05	9.31	10.23
	GT1AO2	1.97	7.28	9.73	10.82
	Log. Av.	1.72	7.00	9.35	10.35
Retardation, R2	GT3AP2	1.16	6.13	8.06	8.80
	GT3AP3	1.32	6.07	7.77	8.47
	GT2AP2	1.41	6.34	8.74	9.66
	Log. Av.	1.29	6.18	8.18	8.96

11.0 MPa/g

Sequence	Specimen Number	Number of programs at crack length (2a)				
		15 mm	20 mm	30 mm	40 mm	50 mm
Acceleration, A2	GT2AA2	5.68	15.96	28.15	34.07	37.02
	GT3AR3	5.86	16.87	29.41	35.44	38.58
	GT3AO2	5.94	17.75	30.52	36.98	40.22
	Log. Av.	5.83	16.85	29.34	35.48	38.58
Retardation, R2	GT1AN3	5.69	17.30	28.29	33.76	36.65
	GT2AR3	5.70	15.98	26.93	32.52	35.27
	GT3AO1	5.98	17.93	29.40	34.94	37.71
	Log. Av.	5.79	17.05	28.13	33.73	36.53

TABLE 4

CRACK GROWTH LIVES OF CENTRE-CRACKED SPECIMENS AT SEVERAL CRACK LENGTHS FOR THE F-B-F AND RANDOM SEQUENCES

17.0 MPa/g

Sequence	Specimen Number	Number of programs at crack length (2a)			
		15 mm	25 mm	35 mm	45 mm
Flight-by-flight	GT2AR1	1.13	4.67	6.31	7.14
	GT1AN1	1.21	4.65	6.39	7.28
	GT1AR2	1.27	4.90	6.58	7.56
	Log. Av.	1.20	4.74	6.43	7.32
Random	GT1AN2	0.80	4.14	5.92	6.74
	GT3AO3	1.10	4.91	6.74	7.71
	GT1AO1	1.19	4.52	6.11	6.73
	Log. Av.	1.02	4.51	6.25	7.04

11.0 MPa/g

Sequence	Specimen Number	Number of programs at crack length (2a)				
		15 mm	20 mm	30 mm	40 mm	50 mm
Flight-by-flight	GT2AO3	3.63	10.33	17.49	21.92	23.84
	GT2AP3	4.01	11.55	19.56	23.93	26.00
	GT3AM1	4.40	12.68	21.75	26.57	28.83
	Log. Av.	4.00	11.48	19.53	24.06	26.15
Random	GT1AB2	3.18	9.57	16.80	20.73	22.86
	GT3AM3	3.30	10.17	18.42	22.85	25.23
	GT3AR1	3.97	11.38	19.51	24.30	26.59
	Log. Av.	3.47	10.35	18.21	22.58	24.84

Wing micro-strain values

Peak level	-520	-340	-160	20	200	380	560	740	920	1100	1280	1460	1640	
2	0													-340
3	0	0												-160
4	0	0	0											20
5	0	0	0	149										200
6	1	0	91	9523	2198									380
7	1	22	2318	21601	2805	1591								560
8	0	37	659	810	1873	1665	705							740
9	1	18	131	575	1209	521	896	124						920
10	0	17	72	421	609	302	306	336	110					1100
11	3	24	42	400	338	23	131	168	183	147				1280
12	5	25	60	516	171	1	92	39	63	71	97			1460
13	9	9	18	16	53	0	11	0	0	11	1	35		1640
14	1	0	0	0	0	0	0	0	0	0	0	0	0	1820
Trough level →	1	2	3	4	5	6	7	8	9	10	11	12	13	

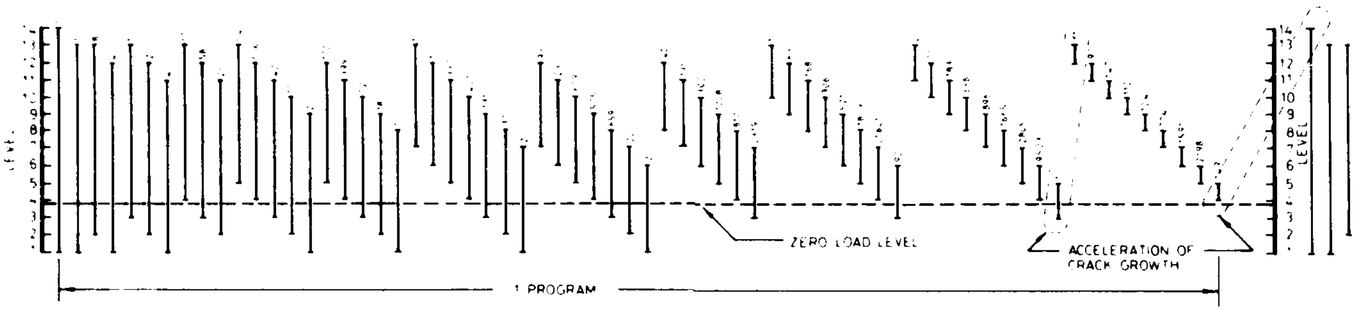
FIG. 1 RANGE-PAIR TABLE FOR MIRAGE III 0 WING TEST SEQUENCE, DISCRETIZED TO 14 LEVELS

Peak level	Trough level 1	2	3	4	5	6	7	8	9	10	11	12	13
2	0												
3	0	0											
4	0	0	0										
5	0	0	0	149									
6	1	0	91	9523	2198								
7	1	22	2318	21601	2805	1591							
8	0	37	659	810	1873	1665	705						
9	1	18	131	575	1209	521	896	124					
10	0	17	72	421	609	302	306	336	110				
11	3	24	42	400	338	23	131	168	183	147			
12	5	25	60	516	171	1	92	39	63	71	97		
13	9	9	18	16	53	0	11	0	0	11	1	35	
14	1	0	0	0	0	0	0	0	0	0	0	0	0

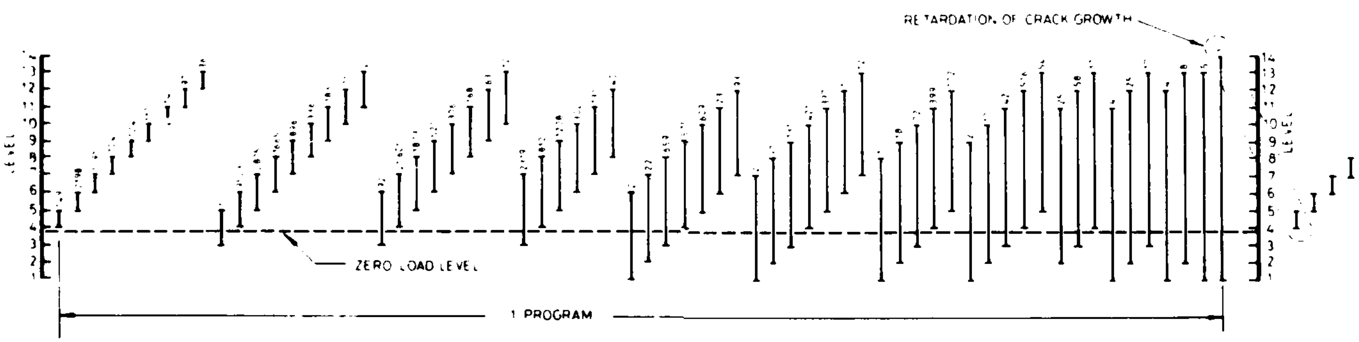
FIG. 2 RANGE-PAIR TABLE SHOWING THE PATH TAKEN IN CONSTRUCTING 'ACCELERATION' SEQUENCE A1

Peak level	Trough level 1	2	3	4	5	6	7	8	9	10	11	12	13
2	0												
3	0	0											
4	0	0	0										
5	0	0	0	149									
6	1	0	91	9523	2198								
7	1	22	2318	21601	2805	1591							
8	0	37	659	810	1873	1665	705						
9	1	18	131	575	1209	521	896	124					
10	0	17	72	421	609	302	306	336	110				
11	3	24	42	400	338	23	131	168	183	147			
12	5	25	60	516	171	1	92	39	63	71	97		
13	9	9	18	16	53	0	11	0	0	11	1	35	
14	1	0	0	0	0	0	0	0	0	0	0	0	0

FIG. 3 RANGE-PAIR TABLE SHOWING THE PATH TAKEN IN CONSTRUCTING 'RETARDATION' SEQUENCE R1

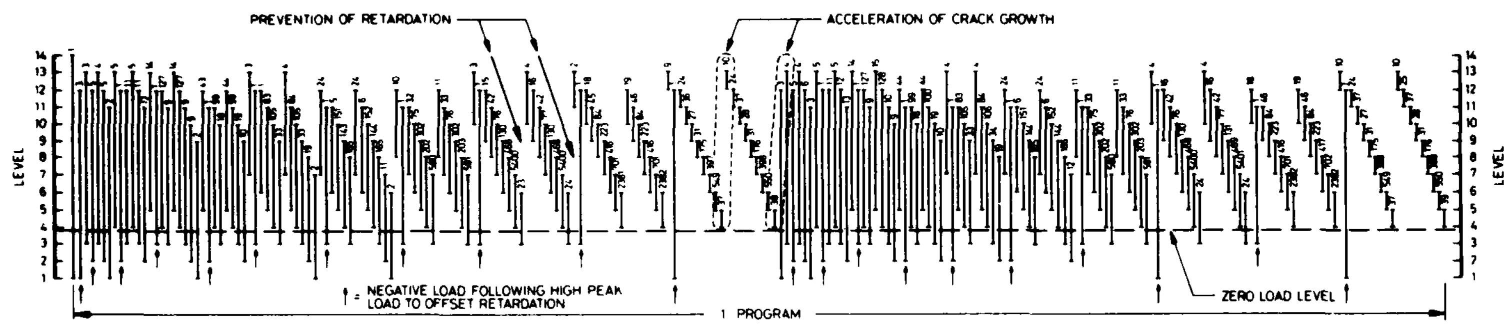


(a) Sequence A1

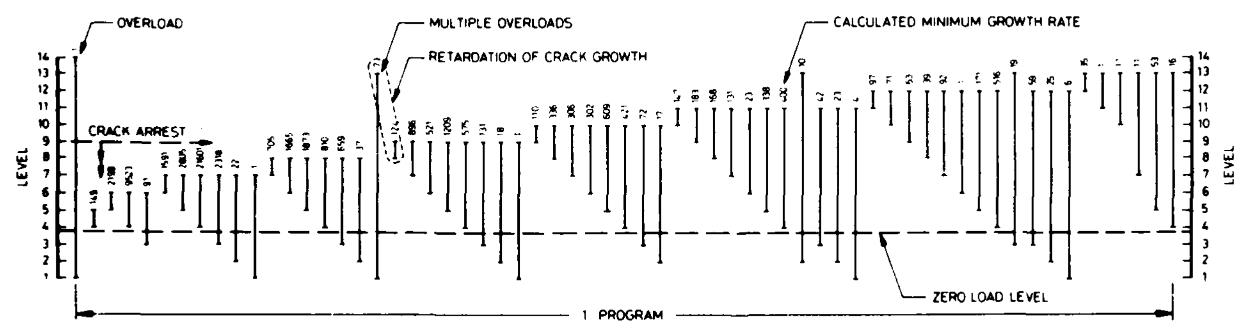


(b) Sequence R1

FIG. 4 REPRESENTATION OF SEQUENCES A1 AND R1 (Numbers refer to the cycles applied at the ranges shown)

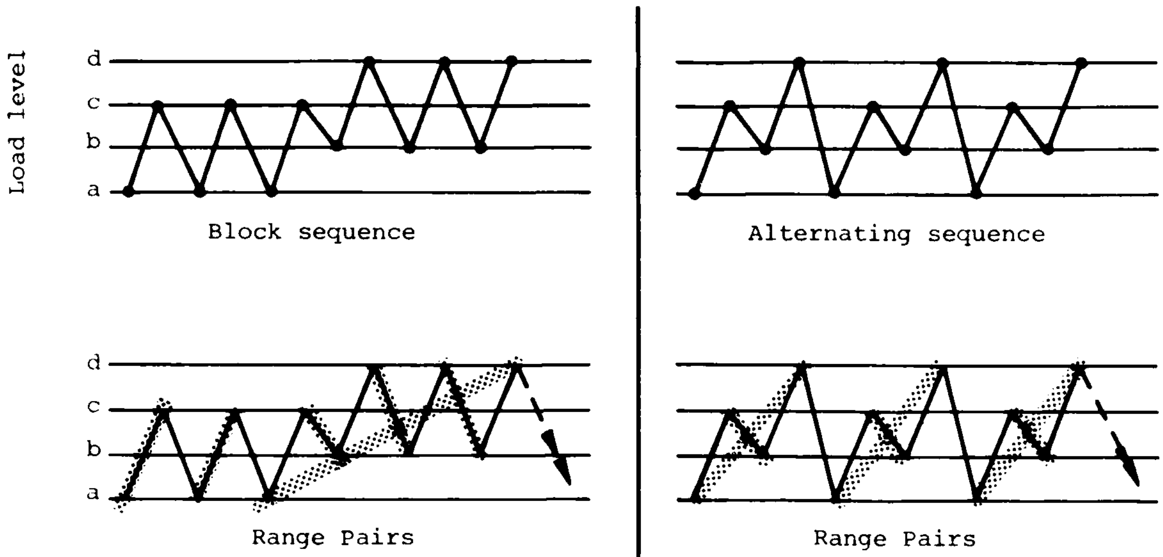


(a) Sequence A2



(b) Sequence R2

FIG. 5 REPRESENTATION OF SEQUENCES A2 AND R2 (Numbers refer to the cycles applied at the ranges shown)



Range Pairs

Peak	Trough	No.
c	a	2
d	b	2
c	b	1
d	a	1

Range Pairs

Peak	Trough	No.
c	b	3
d	a	3

FIG. 6 SEQUENCE EFFECTS ON RANGE-PAIR COUNTS

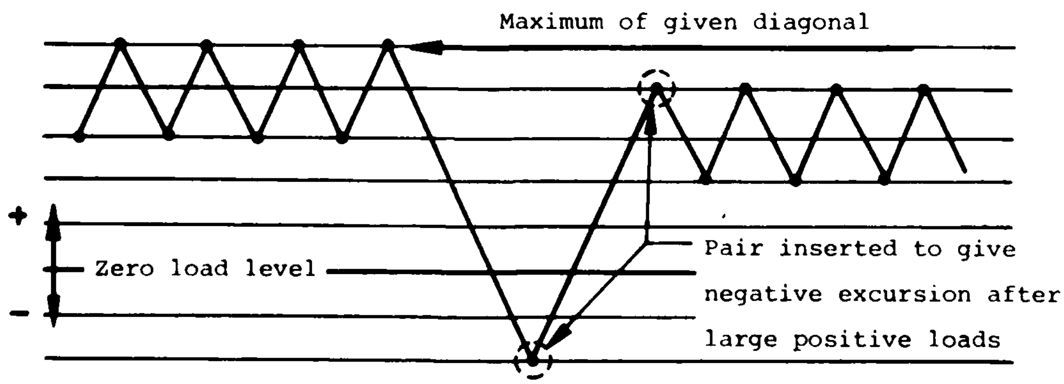


FIG. 7 INSERTION OF NEGATIVE LOAD TO PREVENT CRACK GROWTH RETARDATION

Peak level ↓ / Trough level →	1	2	3	4	5	6	7	8	9	10	11	12	13
2	0												
3	0	0											
4	0	0	0										
5	0	0			<1								
6						<2							
7							<3						
8								<4					
9	1	18	131	575	1209	521	898	124	<5				
10	0	17	72	421	609	302	306	336	110	<6			
11	3	34	43	400	338	23	121	168	183	147	<7		
12	5	25	60	516	171	1	92	39	63	71	97	<8	
13	9	9	18	16	53	0	11	0	0	11	1	35	<9
14		0	0	0	0	0	0	0	0	0	0	0	0

FIG. 8 RANGE-PAIR TABLE SHOWING THE PATH TAKEN IN CONSTRUCTING 'RETARDATION' SEQUENCE R2

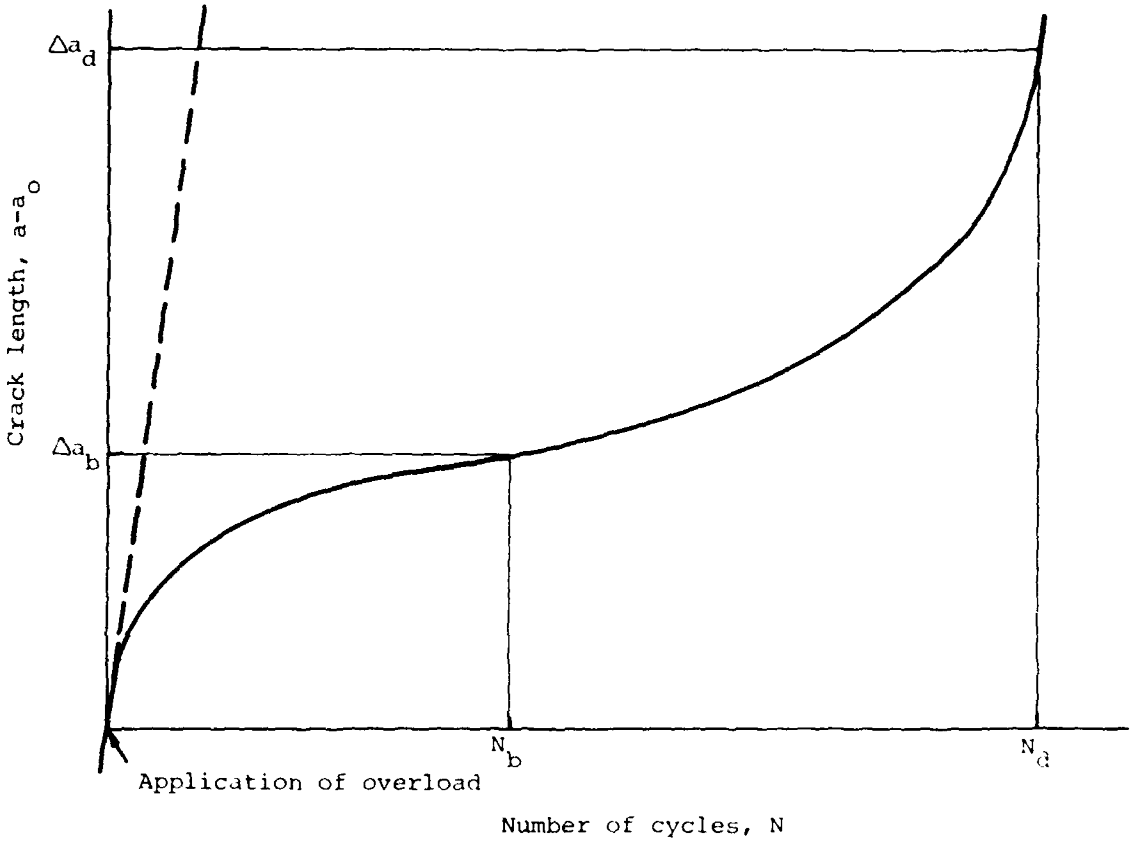


FIG. 9 DELAYED CRACK GROWTH RETARDATION

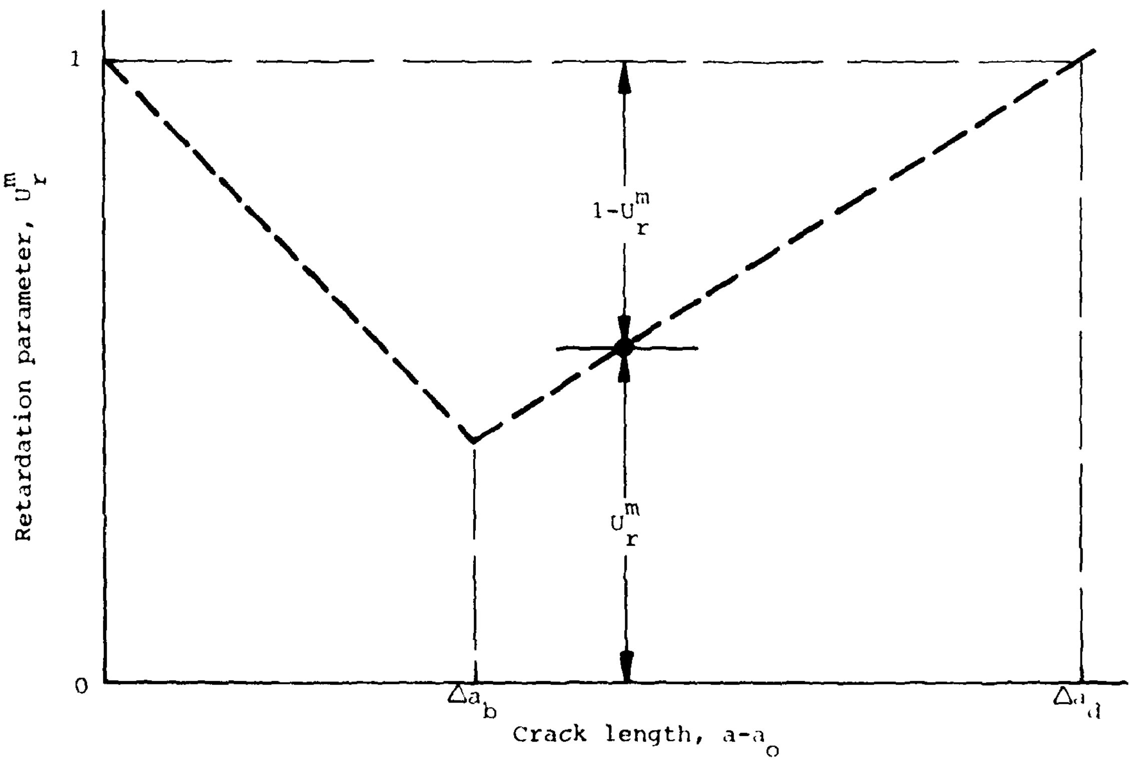


FIG. 10 MODELLING DELAYED RETARDATION

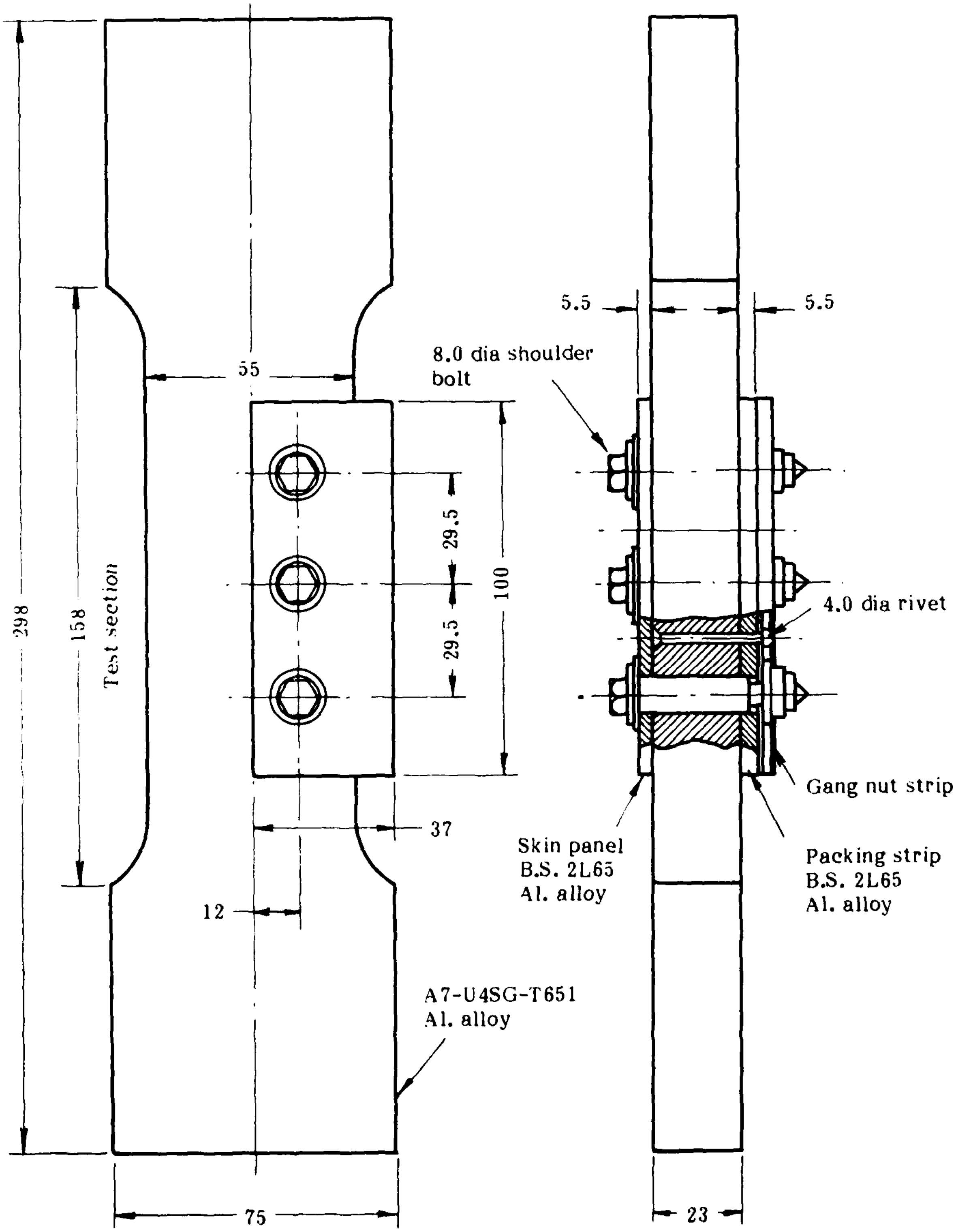


FIG. 11 SIMULATION SPECIMEN (representing lower rear flange of Mirage wing main spar)

FIG. 12 MACROSCOPIC VIEW OF CRACK GROWTH INITIATING AT END BOLT HOLE OF SIMULATION SPECIMEN (GT2AB1) X2

FIG. 13 FATIGUE STRIATION SEQUENCE USED TO IDENTIFY CRACK INCREMENTS FOR SEQUENCE R1 ON SIMULATION SPECIMEN (GT2AB1)

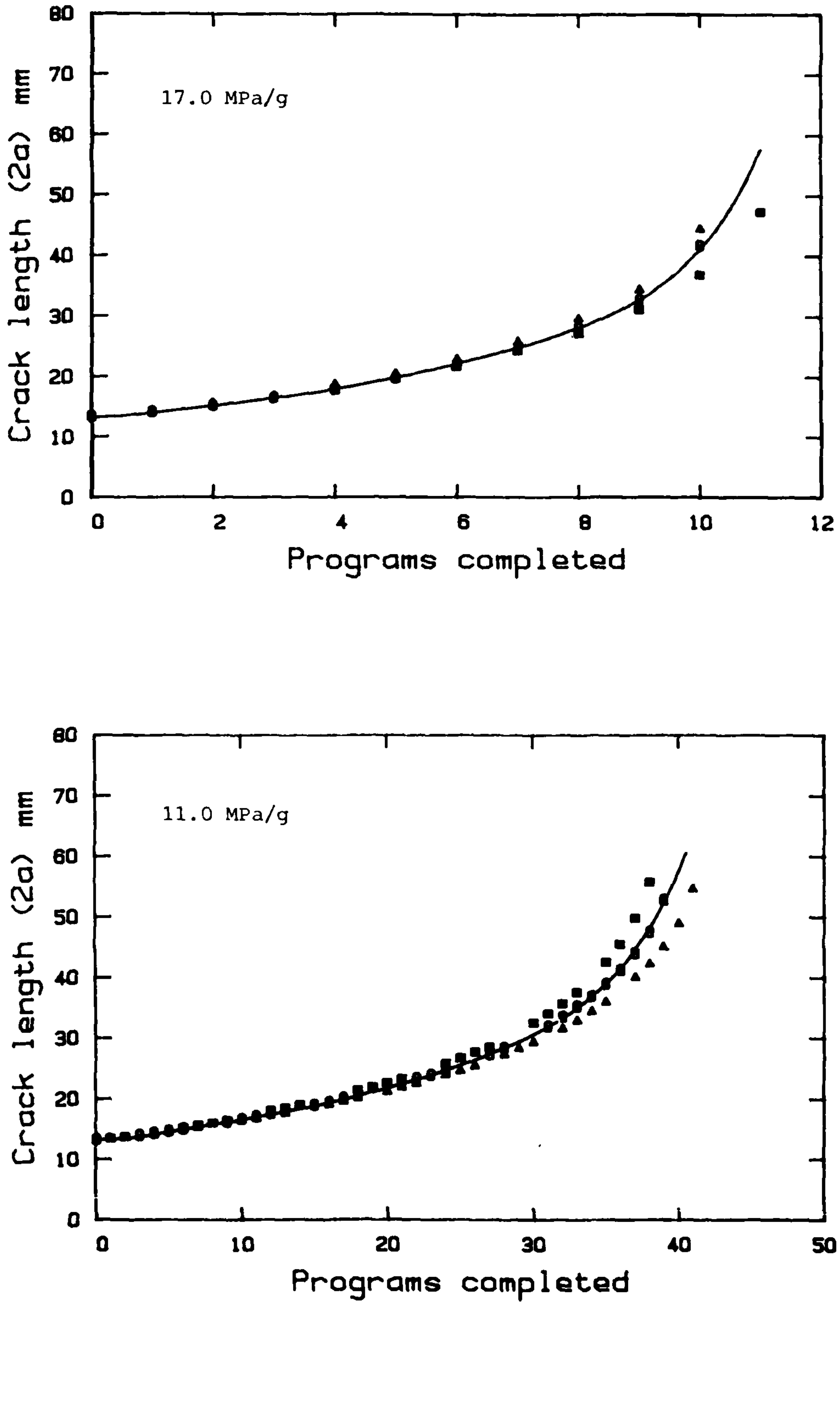
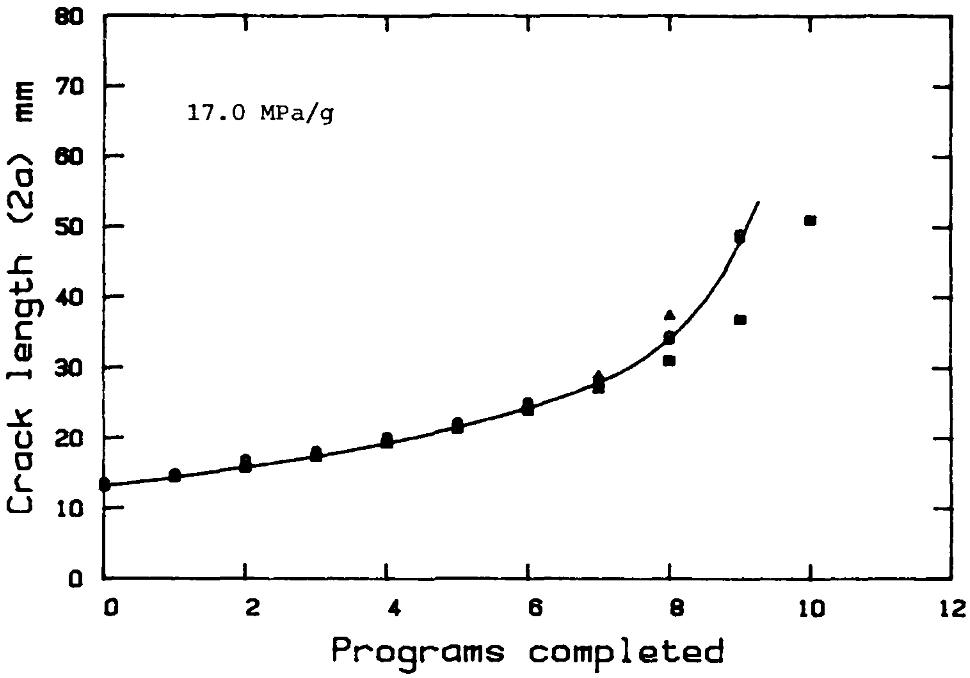


FIG. 14 CRACK GROWTH IN CENTRE-CRACKED SPECIMENS FOR ACCELERATION SEQUENCE A2



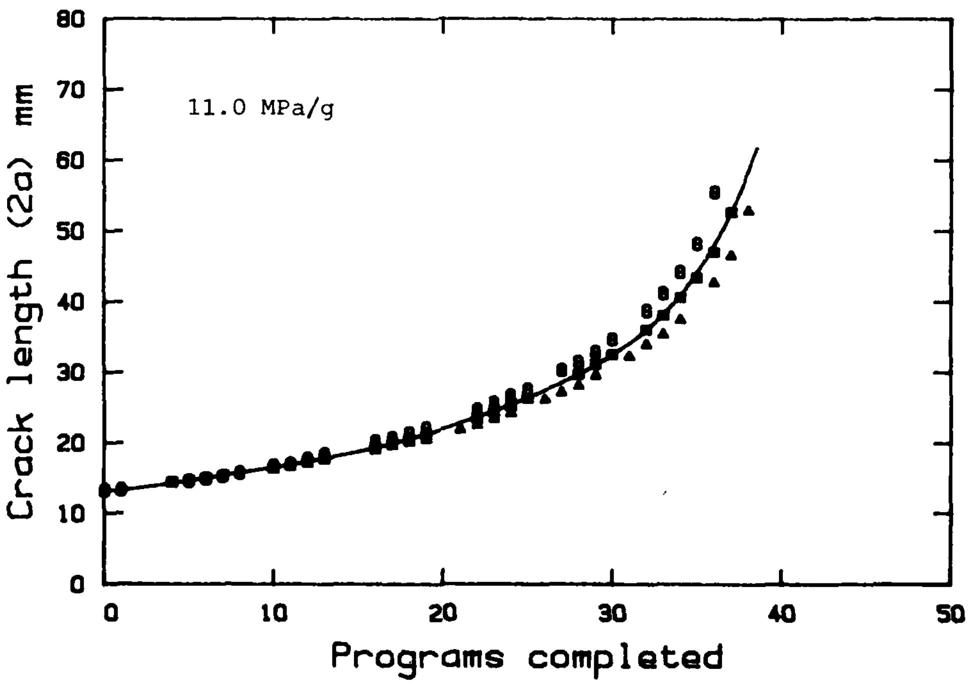


FIG. 15 CRACK GROWTH IN CENTRE-CRACKED SPECIMENS FOR RETARDATION SEQUENCE R2

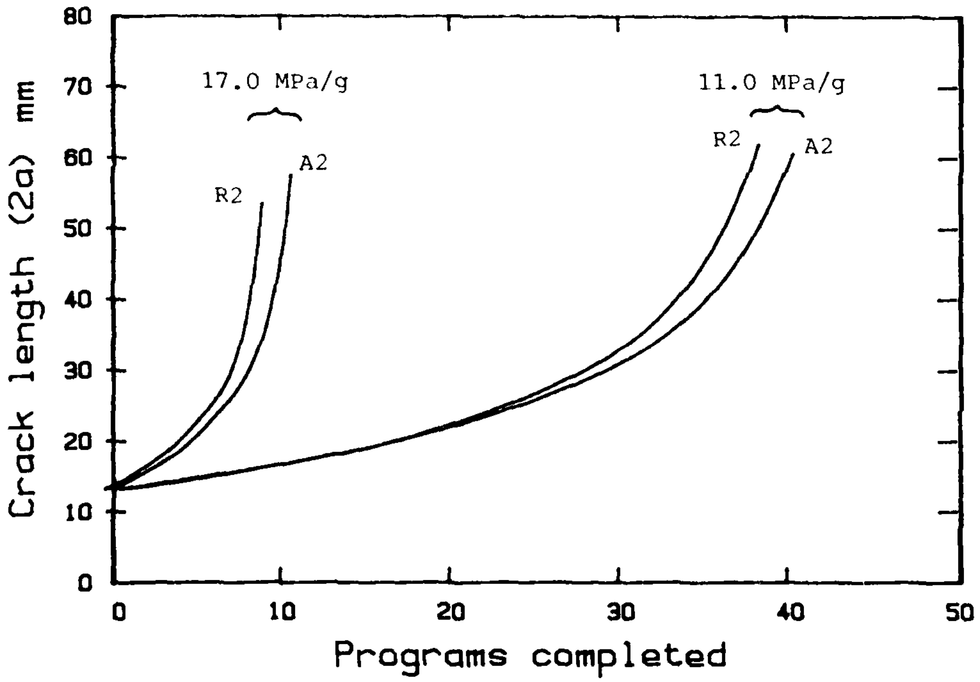


FIG. 16 COMPARISON OF CRACK GROWTHS IN CENTRE-CRACKED SPECIMENS UNDER SEQUENCES A2 AND R2

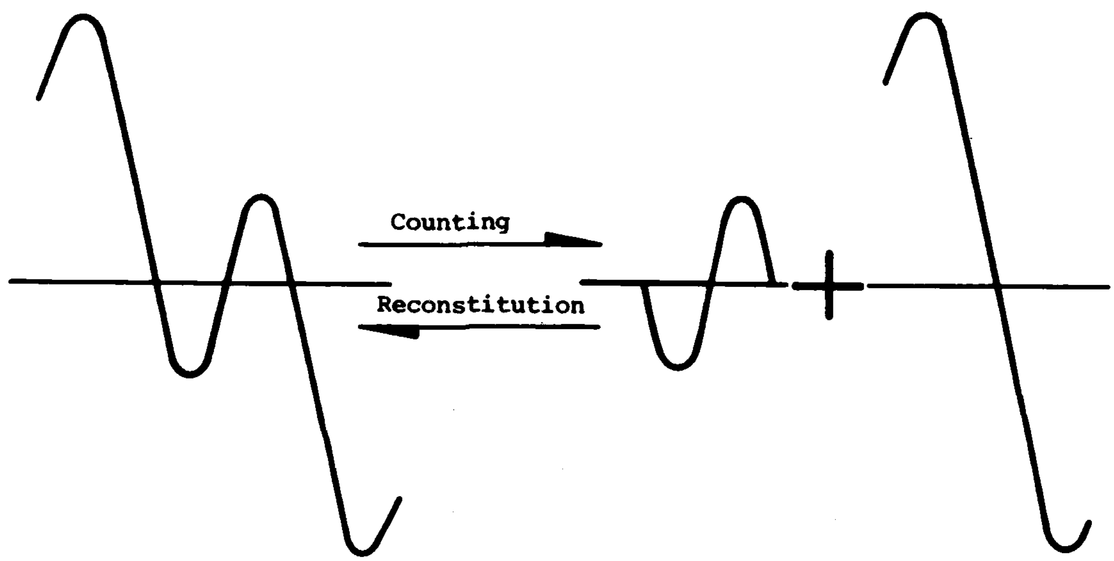
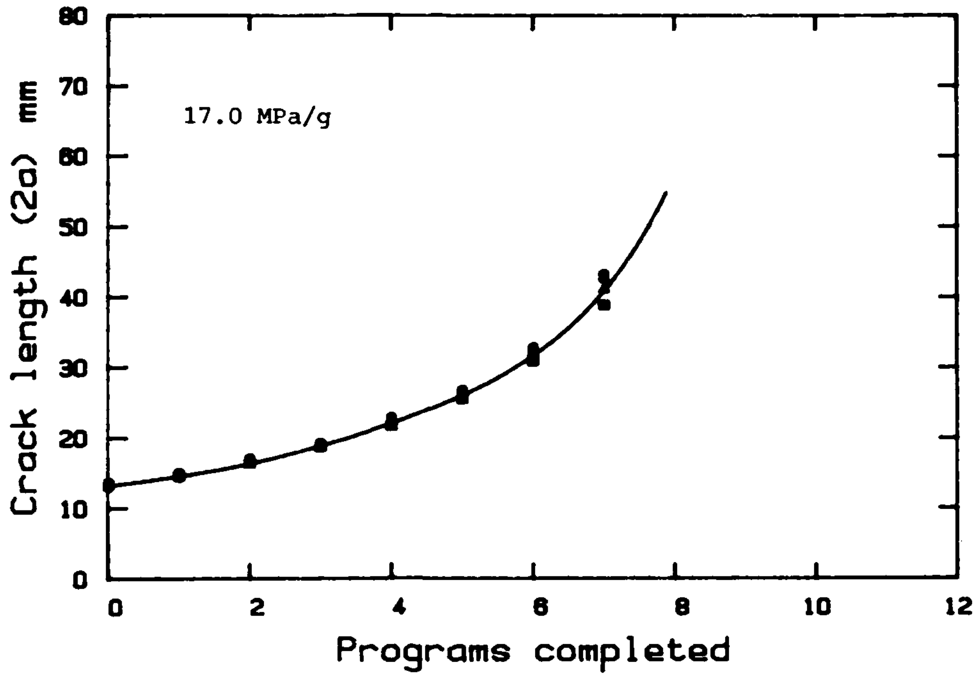


FIG. 17 ESSENCE OF RANGE-PAIR COUNTING AND RANDOM RECONSTITUTION



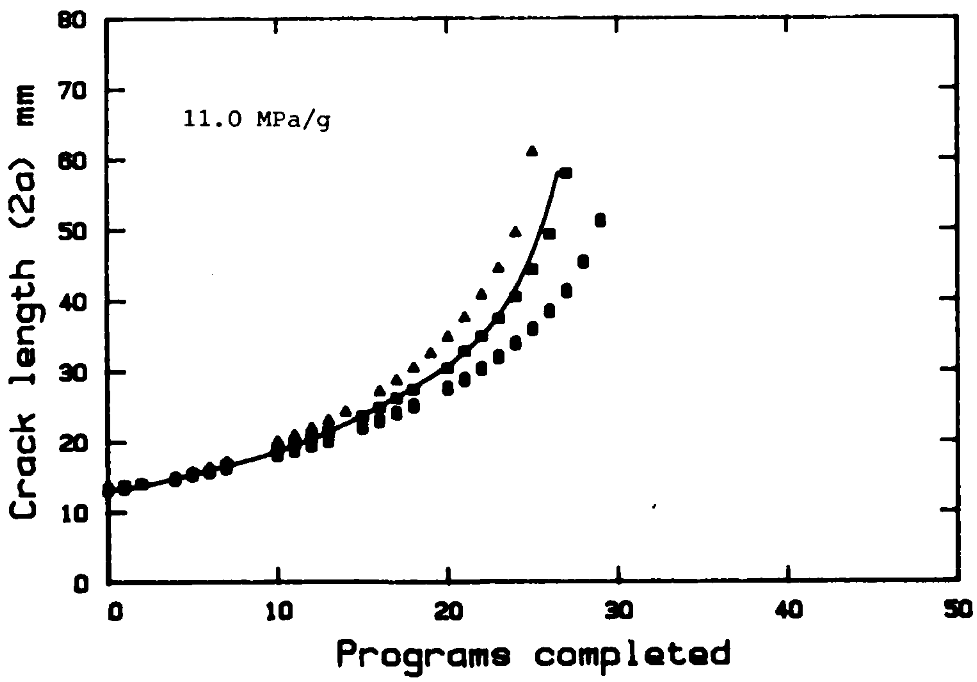


FIG. 18 CRACK GROWTH IN CENTRE-CRACKED SPECIMENS FOR THE FLIGHT-BY-FLIGHT SEQUENCE

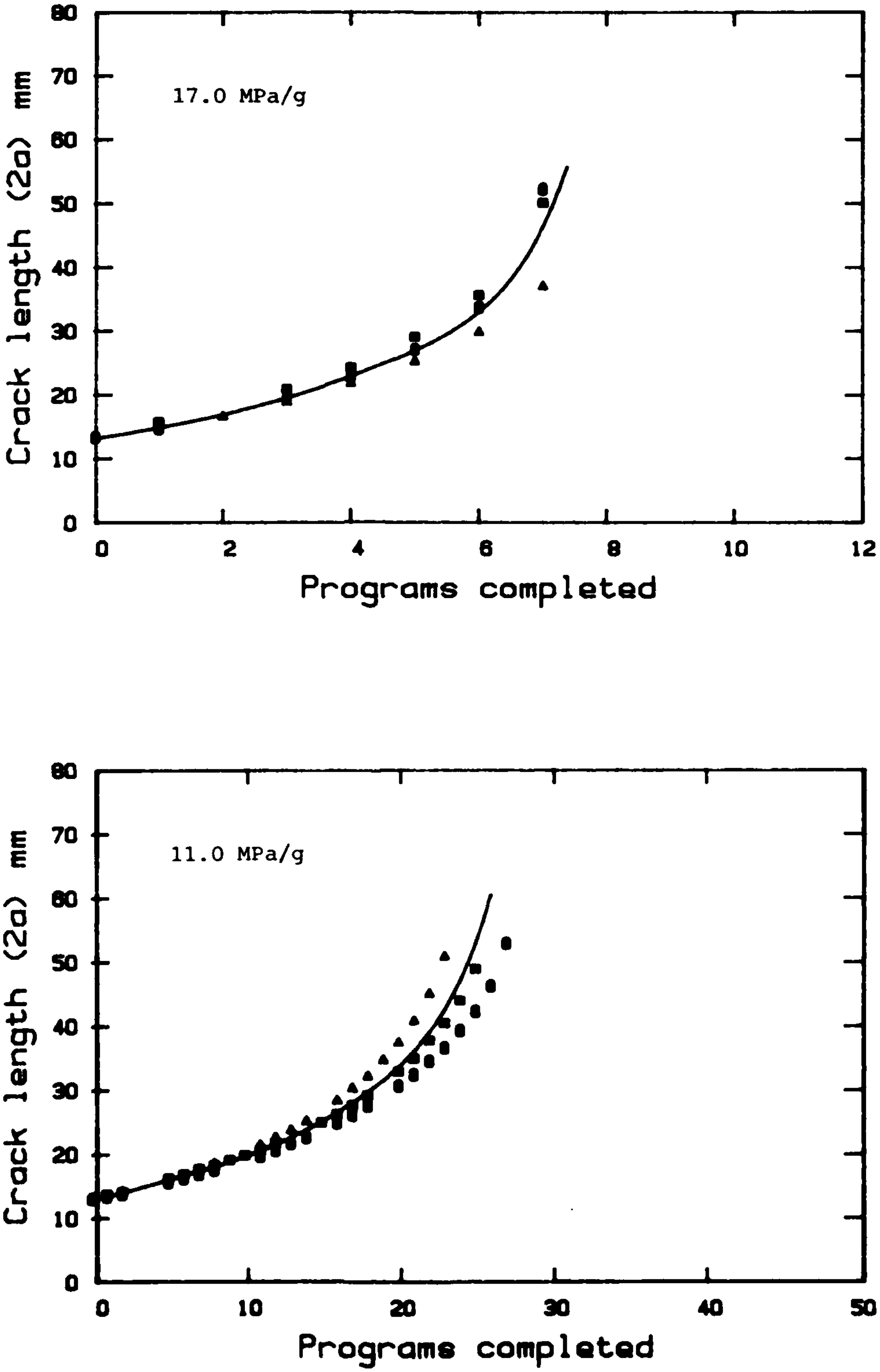


FIG. 19 CRACK GROWTH IN CENTRE-CRACKED SPECIMENS FOR RANDOM SEQUENCES

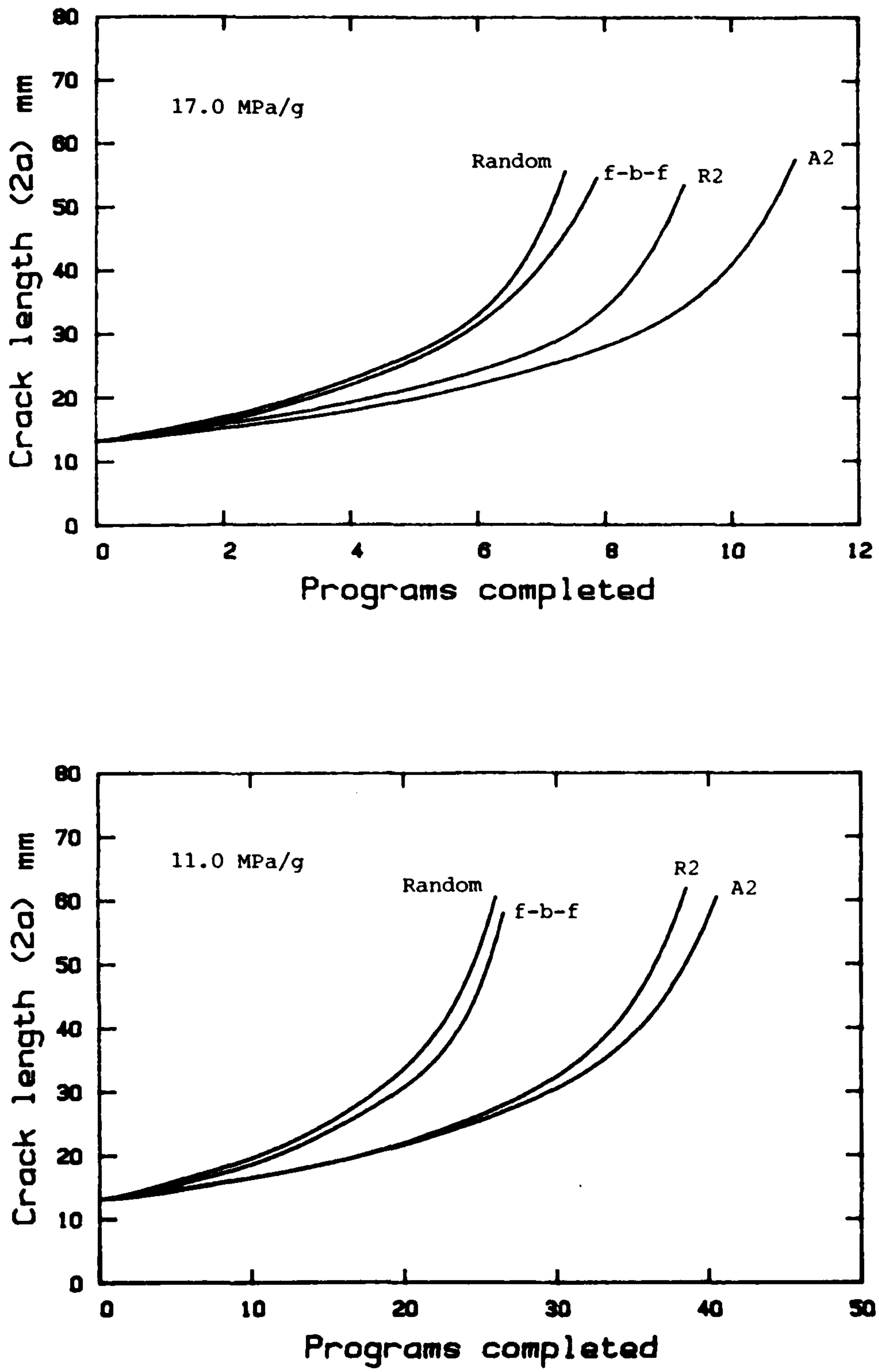


FIG. . CRACK GROWTH IN CENTRE-CRACKED SPECIMENS UNDER FOUR SEQUENCES ALL HAVING IDENTICAL RANGE-PAIR COUNTS

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16. Abstract

Fatigue experiments have been conducted to assess the influence of the method of reconstituting a load sequence from a range-pair counted load spectrum for a fighter aircraft. In addition to the original flight-by-flight sequence, several quite-structured reconstituted sequences and random reconstituted sequences were used, all sequences having identical range-pair counts. There was little or no difference in crack propagation lives or total lives of two specimen geometries for the several structured sequences which were designed to give the extremes in crack growth life. There was, also, no significant difference in crack propagation lives for specimens tested under the flight-by-flight and randon sequences. Crack growth under the more-structured sequences was significantly slower than under the more-fluctuating sequences (random and flight-by-flight), although the maximum difference of 1.59:1 is small relative to other uncertainties in fatigue life assessment. These results provide a basis for implementing the Aircraft Fatigue Data Analysis System which utilizes strain range-pair counting. (Keywords) :

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